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LCI METHODOLOGY AND DATABASES

Life cycle inventory analysis of granite production from cradle to gate

Joan-Manuel F. Mendoza · Maria Feced · Gumersindo Feijoo · Alejandro Josa · Xavier Gabarrell · Joan Rieradevall

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Abstract
Purpose Granite is a traditional high-quality material that is widely used in construction. A key strategy that is increasingly promoted to highlight the competitiveness of materials is life cycle environmental performance. Due to the lack of comprehensive life cycle inventories (LCIs), the environmental characterisation of granite products has received little attention in scientific literature. In this paper, a complete LCI of the production chain of intermediate and finished granite products is provided and analysed.
Methods The Spanish granite production industry, which is the second major European producer and the seventh worldwide, is examined. The reference unit is defined as 1 m^2 of finished granite tiles with dimensions 60×40×2 cm used for indoor and outdoor applications. Input and output data were collected through the distribution of technical data collection surveys to quarries and processing facilities and via on-site visits. During data calculation and validation, technical support was provided by technicians from the Spanish Cluster of Granite Producers. The LCI data describe the industrial activity in baseline year 2010 that corresponds to a total production volume of 48,052 m^3 of quarried granite and a net of 881,406 m^2 of processed granite.
Results and discussion The production of 1 m^2 of polished granite tiles requires 28 kWh of electricity, 23 MJ of diesel, 103 l of water, and 7 kg of ancillary materials. Sandblasted, flamed or bush-hammered finishes applied to granite tiles have a minimal effect on their total energy and material requirements but significantly affect their water consumption. Electrical energy, cooling water and steel are the major industrial requirements in which granite sawing is the most demanding process. The resource efficiency of the production chain is 0.31. Approximately 117 kg of granite are wasted per square meter of granite tiles that are produced (53 kg). Seventy-four percent of granite waste is composed of granite scrap, which becomes a marketable by-product. The predominant source of granite waste is the sawdust that is generated during stone-cutting operations.
Conclusions LCIs provide the relevant information required to characterise the environmental performance of granite production and products. LCI data can be easily managed by users due to the disaggregation into unit processes. LCI data can be used to analyse the environmental burden associated with intermediary granite products, such as granite blocks, sawn granite slabs and finished granite slabs, and to analyse

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J.-M. F. Mendoza (✉) · M. Feced · X. Gabarrell · J. Rieradevall
Sostenipra (ICTA-IRTA-Inèdit), Institute of Environmental Science and Technology (ICTA), School of Engineering (ETSE), Universitat Autònoma de Barcelona (UAB), Campus de la UAB, Bellaterra (Cerdanyola del Vallès), 08193 Barcelona, Catalonia, Spain
e-mail: joanmanuel.fernandez@uab.cat

G. Feijoo
Department of Chemical Engineering, School of Engineering, University of Santiago de Compostela, 15782 Santiago de Compostela, Galicia, Spain

A. Josa
Institute of Sustainability (IS.UPC), Technical University of Catalonia-Barcelona Tech (UPC), Campus Nord, Building VX, Plaça Eusebi Güell, 6, 08034 Barcelona, Catalonia, Spain

A. Josa
Department of Geotechnical Engineering and Geosciences, School of Civil Engineering (ETSECCPB), Technical University of Catalonia-Barcelona Tech (UPC), Campus Nord, C/Jordi Girona 1-3, Building D2, 08034 Barcelona, Catalonia, Spain

X. Gabarrell · J. Rieradevall
Department of Chemical Engineering, School of Engineering (ETSE), Universitat Autònoma de Barcelona (UAB), Campus de la UAB, Bellaterra (Cerdanyola del Vallès), 08193 Barcelona, Catalonia, Spain

the environmental burden of finished granite tiles according to the corresponding net production volumes.
Recommendations LCI dataset of granite production should be extended to include alternative production technologies, such as diamond multiwire machines for sawing granite, which is an increasingly competitive production technology with interesting properties for cleaner production. Strong competitive granite industries, such as the industries in China, India and Brazil, should also provide LCIs of granite products to transparently compare different product chains, identify environmental strategies on the sector level, and promote the green procurement of granite products.

Keywords Environmental performance · Granite · LCI · Natural stone · Quarrying · Resource efficiency · Sawing · Slabs

1 Introduction

The European Union (EU) is an important producer and consumer region of natural stone. In 2008, the EU produced over 24 million tonnes of finished natural stone products. The biggest producer region is located in southern Europe, in which Italy and Spain produce nearly 70 % of the total production in the EU (CBI 2010). Spain is ranked second in the EU with regards to production and consumption of natural stone products. From 1993 to 2009, the average production volume of natural stone in Spain exceeded 6,283 kt: 66 % marble (4,149 kt), 22 % granite (1,386 kt), and 12 % slate (748 kt). Although granite is the second largest natural stone that is quarried and processed in the country, it possesses a significant economic value in the domestic industry and is vital to the regional and international market. Spain is the seventh largest global exporter of gross granite and the fifth largest global exporter of finished granite with market shares of 3.5 and 2.9 %, respectively. Spain is also the fourth largest importer of gross granite, which accounts for a global share of 5.7 %; however, it rarely imports finished granite products as the demand is primarily satisfied by the domestic industry (OMPN 2009, 2010, 2011). The Spanish granite industry is mature, highly specialised and competitive.

Granite is a traditional high-quality material that is widely used in construction due to its hardness, durability and aesthetic properties. Granite materials exhibit high performance in atmospheric and acoustic insulation and construction protection, as well as high impermeability, resistance to abrasion and chemical attack, resistance to wear and fire, resistance to light- and medium-weight traffic loads, resistance to slipping and resistance to an attack of atmospheric agents (FDP 2005). As a result, granite competes with many construction materials for various indoor and outdoor applications, such as ceramics in indoor paving; concrete and asphalt in outdoor paving; aluminium, brick and precast concrete in cladding; as well as other diverse uses of materials for ornamental and decoration purposes. A key strategy that is increasingly promoted for highlighting the competitiveness of materials is to demonstrate their life cycle environmental performance and their potential for minimising environmental impacts. Several research studies have underlined the relevance of promoting the use of environmentally suitable construction materials and components to improve the environmental rank of buildings and constructed assets as a whole (Oliver-Solà et al. 2009; Santero and Horvath 2009; Santero et al. 2011; Franzitta et al. 2011; Zabalza et al. 2011). Unlike other competitive construction materials, the analysis of the environmental implications of granite quarrying and processing from a product life cycle approach has received little attention in scientific literature. One major limitation is the lack of complete and comprehensive life cycle inventories (LCI) of granite production and products. Environmental studies of granite production mainly focus on the characterisation of granite wastes generated by the industry and the identification of strategies for their use as by-products in industrial applications (Torres et al. 2004; Silva et al. 2005; Delgado et al. 2006; Almeida et al. 2007; Papantonopoulos et al. 2007; Dhanapandian and Gnanavel 2009; Barrientos et al. 2010; Hamza et al. 2011). Other environmental studies have examined the natural stone industry with a focus on the characterisation of general sustainable indicators and energy saving strategies (Maponga and Munyanduri 2001; Zografidis et al. 2007; Founti et al. 2010). The development of LCIs and the analysis of the environmental performance of natural stone have already been carried out for marble products (Nicoletti et al. 2002; Liguori et al. 2008; Traverso et al. 2010; Gazi et al. 2012), but the granite production chain has not been consistently addressed and evaluated from an environmental standpoint. Only two LCIs of granite products are publicly available and few scientific articles detail the environmental characterisation of granite production from a product life cycle approach. An LCI related to granite production can be found in Kellenberger et al. (2007). Data are provided per kilogram of cut, grounded and polished granite plate with dimensions 50×50×3 cm. Only a few procedures and technologies for granite quarrying and processing are considered, and all data are predominantly based on estimations from different sources. The most comprehensive LCI of granite production was published by the Natural Stone Council (NSC) of the USA 2009 (NSC 2009). This LCI characterises granite quarrying and processing operations in North America based on the production of 1 ft^3 of granite products. This LCI was utilised by different authors to characterise the environmental performance of granite compared with competing products for different applications. The Center for Clean Products of the University of Tennessee (CCP 2009) evaluated the environmental performance of granite as a cladding material for application in a two-story

commercial building and results were compared to the use of aluminium, brick, limestone and precast concrete. Mendoza et al. (2012a, b) conducted a comparative analysis of the life cycle environmental impacts associated with the production and use of granite, concrete and asphalt for outdoor paving. The LCI was also employed as a reference by Crishna et al. (2011) who analysed the embodied energy and CO_2 emissions in the production of dimension stone in the UK. However, the LCI from the NSC (2009) is representative of the production of granite in the context of the geography, regulatory framework, and technological and economic markets of North America. LCI data also reflect the inputs and outputs per cubic feet of granite quarrying and processing, in which an array of cutting operations, finishing applications and shaping operations of a combination of granite products are included. The LCI from NSC (2009) provides a complete overview of the average energy, water and material flows associated with the US granite industry. However, due to the complexity of the aggregation of the data, the adaptation of the inputs and outputs to the environmental assessment of a specific granite product and the analysis of the contribution to the energy, water and material demands, as well as waste generation, of the different unit processes and the intermediary products of the granite production chain prove challenging. To transparently determine the environmental performance of granite products and to identify strategies for environmental improvement, the development of complete, comprehensive and disaggregated LCIs are essential.

Recognising that the demand for sustainable construction materials is becoming increasingly critical to the marketplace, the Spanish Cluster of Granite Producers (SCGP) began a research project in 2011 that aims to enhance the understanding of the production chain and the consumption of granite products by providing information about their environmental performance. This paper presents a comprehensive LCI of the Spanish production chain of granite. The LCI data presented aims to contribute to the characterization of the environmental hot spots of granite production in order to identify strategies to mitigate negative impacts and promote efficient production of granite products. As the Spanish granite industry ranks second in the European ranking of granite producers, the LCI data provided may act as a representation of the inputs and outputs related to the production of granite in Europe, especially in southern Europe.

2 Methods

The life cycle inventory analysis was addressed by following the guidelines specified by the ISO 14044 (2006).

2.1 Functional unit

The unit reference for estimating the inputs and outputs related to the granite production chain was defined as 1 m^2 of finished granite tiles with dimensions of $60\times40\times2$ cm, which are standard pieces applied in construction. Granite tiles with thicknesses of 2 cm are typically used for indoor flooring and cladding; however, they can also be used as outdoor paving materials in environments with low- and light-weight traffic (i.e. pedestrian areas) or as outer cladding materials for aesthetic purposes. Depending on the application of granite tiles, a specific finish on the surface of the material is required. Four different surface finishes have been considered to characterise the variation in the energy, water and material demands of granite tiles. A brief description of the different unit processes of the granite production chain is presented in Section 2.2.2.

2.2 System boundaries

2.2.1 Geographical, production volume and time-related coverage

The production of granite in the region of Galicia in Northwest Spain is the geographical context in the analysis. The region of Galicia represents over 60 % of the national volume of granite quarrying and processing. By focusing on foreign trade, Galicia monopolises the export and import markets of domestic gross granite with 92 % (229 kt) and 79 % (368 kt) of the share, respectively. The province of Pontevedra (Southwest Galicia) is the principal producer area of the region as 90 % of the total volume of Galician granite production (244 kt) is exported from this province, which also ranks first among importers of granite with 76 % of the total importation (353 kt). It is also the area in which "Rosa Porriño", which is one of the predominant types of granite, is produced (OMPN 2011). The industrial activities of three quarries and three processing facilities from the area of O Porriño in Pontevedra (Galicia, Spain) have been evaluated. The quarries comprise 31 % of the total volume of quarried granite in Galicia, whereas the processing facilities comprise 20 % of the total volume of processed granite. On a national scale, quarries and processing facilities account for 17 and 16 % of the total production volumes, respectively (personal communication, SCGP 2012). The total net production volume that was analysed consists of 48,052 m^3 (≈130 kt) of quarried granite and 881,406 m^2 (≈48 kt) of processed granite. Production volumes refer to the industrial activity of 2010. Electronic Supplementary Material (ESM) 1 shows a description of the production volumes of each of the quarries and processing facilities that were analysed.

2.2.2 Description of the production chain and technological coverage

A simplified diagram of the basic unit processes and operations of the production chain of granite tiles is shown in Fig. 1.

Granite quarrying Quarrying operations consist of the extraction of large benches, subdivision into primary blocks, subdivision into commercial blocks, and storage and transportation. A combination of drilling, blasting and cutting operations is applied. Granite quarrying starts by drilling boreholes (1) for the subsequent passage of the diamond wire (2) to begin cutting the vertical planes of the bench. The boreholes are created by using probe drives that are driven by air compressors powered by diesel. Electric-powered diamond monowire machines are used for cutting the stone. A series of boreholes are created along the perimeter of the ground plane and filled with gun powder and detonating cord (3) to separate the granite bench from the ground. The granite bench is subdivided into primary granite blocks by the application of drilling and blasting (4a) or cutting (4b) techniques. In the first case, pneumatic hammers driven by electrically powered air compressors or diesel-powered backhoes equipped with drills are employed. A small amount of gun powder and/or a detonating cord are also applied. The second technique is based on the use of diamond monowire machines. The primary granite block is dumped on the ground of the quarry (5) by using backhoes equipped with mechanical arms. A diesel-powered loader is employed to prepare a sand or clay bed (6) to prevent stone breakage. The primary granite block is subdivided into commercial granite blocks by drilling a series of boreholes (7) using hydraulic hammers driven by a compressed air circuit. Steel shims and wedges are introduced in the boreholes to break the stone. The granite blocks are squared (8) using pneumatic hammers and/or diamond wire. The granite blocks have suitable dimensions for transporting and handling in processing industries. The average dimensions of commercial granite blocks are 1.7 m high, 3 m long and 1.7 m wide (8.67 m^3). Commercial granite blocks are transferred to storage and loaded onto trucks (9) for transportation to processing facilities using diesel-powered loaders. Due to legal concerns, a truck can only transport a single commercial block per voyage.

Granite processing The operations related to granite processing can be divided into three major unit processes: sawing (primary cutting), finishing (surface treatment) and (secondary) cutting (and/or shaping). During the sawing process (10), the granite block is cut into slabs with dimensions defined by the dimensions of the granite block. Their thicknesses, however, are defined by customer demand, which determines the number of granite slabs produced per sawn block. The processing facilities use gang saw machines that are the most widely used technology for the mass production of granite slabs with thicknesses of 2–3 cm. In the gang saw machines, a granite block is eroded by the action of steel blades mounted in a heavy frame, which is moved back and forth at high speeds by a transmission mechanism. Granite slabs can either pass directly to the finishing line (11) to obtain a specific texture on the surface of the stone or bypass the finishing process and go directly to the cutting line once the granite product is determined to have a "natural" appearance. The following finishing

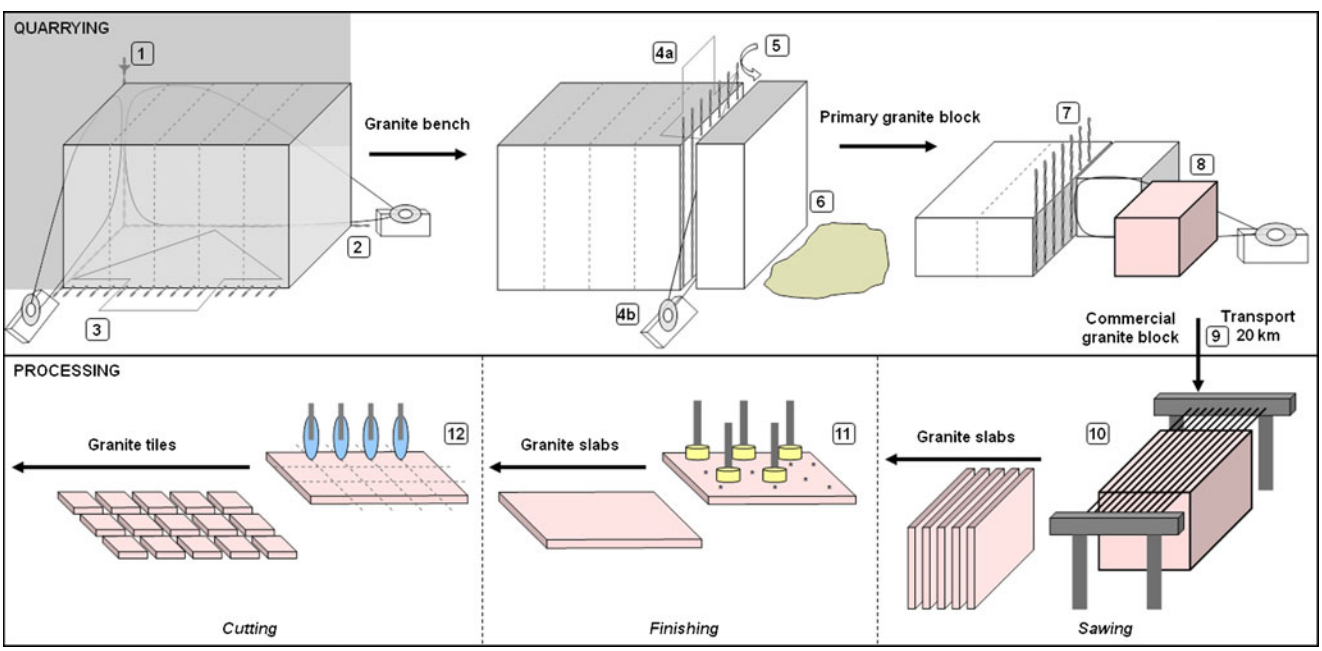

Fig. 1 Simplified diagram of the basic stages of the production chain of granite tiles

processes conducted by the processing facilities are considered in this study:

- *Polishing.* The treatment of the surface of the stone with progressively finer abrasive grains. A smooth and shiny finish surface is generated with almost zero porosity. Polishing is the most common finishing process applied to granite products. Polished granite tiles are used for indoor flooring and indoor and outdoor cladding.
- *Sandblasting.* A sandblasted finish is achieved by projecting silica sand on the surface of the stone. Depending on the pressure applied, the process provides a finer or thicker finished surface. Sandblasted granite tiles are typically used in indoor and outdoor cladding.
- *Flaming.* This process involves the application of a flame on the surface of the stone, which causes the detachment of small chips or splinters. It provides a rough, vitreous, undulating and irregular surface that is resistant to atmospheric chemical alteration. Flamed granite tiles are typically utilised in outdoor paving due to their anti-slipping properties.
- *Bush hammering.* A previously flattened surface is repeatedly hit with jackhammers that contain bushes with small pyramidal teeth. A rough flat and slightly irregular surface is obtained. Bush-hammered granite tiles are mainly applied in outdoor paving due to their anti-slipping properties.

The last step in granite processing consists of cutting the granite slabs (12) into granite tiles of desired dimensions, which is usually accomplished using electric-powered diamond disc saws. Granite tiles are packed using wooden pallets, boards and crates. Steel slings fasteners are also applied.

An extended description of the unit processes, operations and machinery applied in the granite production chain is presented in the ESM 2.

2.3 Inventory analysis

2.3.1 Data collection and quality

The input and output data related to granite production were acquired though the distribution of a technical data collection survey to each of the quarries and processing facilities that participated in the research (ESM 1). The survey was checked, validated and verified by the SCGP, who acted as an intermediary agent. Through a process of data aggregation and analysis between the unit processes (quarrying, sawing, finishing and cutting), insufficient information and the aspects requiring verification by the industrial facilities were identified and additional requirements were established. Once final responses were received, an on-site visit to the quarries and processing facilities supplemented the data collection procedure. Data collected refers to the production volumes and industrial activities of 2010 because it coincides with the outcomes from energy audit reports and industrial and economical balances conducted by the quarries and processing facilities. The considered production technology is modern and widely implemented. The LCI data can be used consistently to characterise the environmental performance of granite production and products in a representative manner.

2.3.2 Data calculation

To provide a complete overview and understanding of the granite production chain, inputs and outputs were calculated in terms of quarrying and processing of an entire granite block into tiles. The LCI of a granite block served as a reference for allocating the inputs and outputs per square meter of finished granite tiles according to the corresponding net production volume. The resource efficiency of each unit process was defined previously to the allocation of inputs and outputs. A granite block of 1.7 m high × 3 m wide × 1.7 m long (8.67 m^3) was considered as the reference unit. ESM 3 describes the factors considered to determine the net production of granite products and wastes per each unit process of the granite processing stage.

3 Results

3.1 Industrial requirements for quarrying and processing an entire granite block into tiles

The energy requirements for quarrying a granite block and processing it into finished tiles are displayed in Table 1. The water and material balances of the granite production chain, which is shown graphically in Fig. 2, were performed using the software Sankey®. Figure 3 summarizes the relative contribution of each unit process to the most significant inputs and outputs of the granite

Table 1 Energy requirements for quarrying and processing an entire granite block into finished tiles

Energy demand	Quarrying	Processing			Total
		Sawing	Finishing (polishing)	Cutting	
Electricity (kWh)	291	3,541	399	2,281	6,512
Diesel (MJ)	5,052	102	95	95	5,343

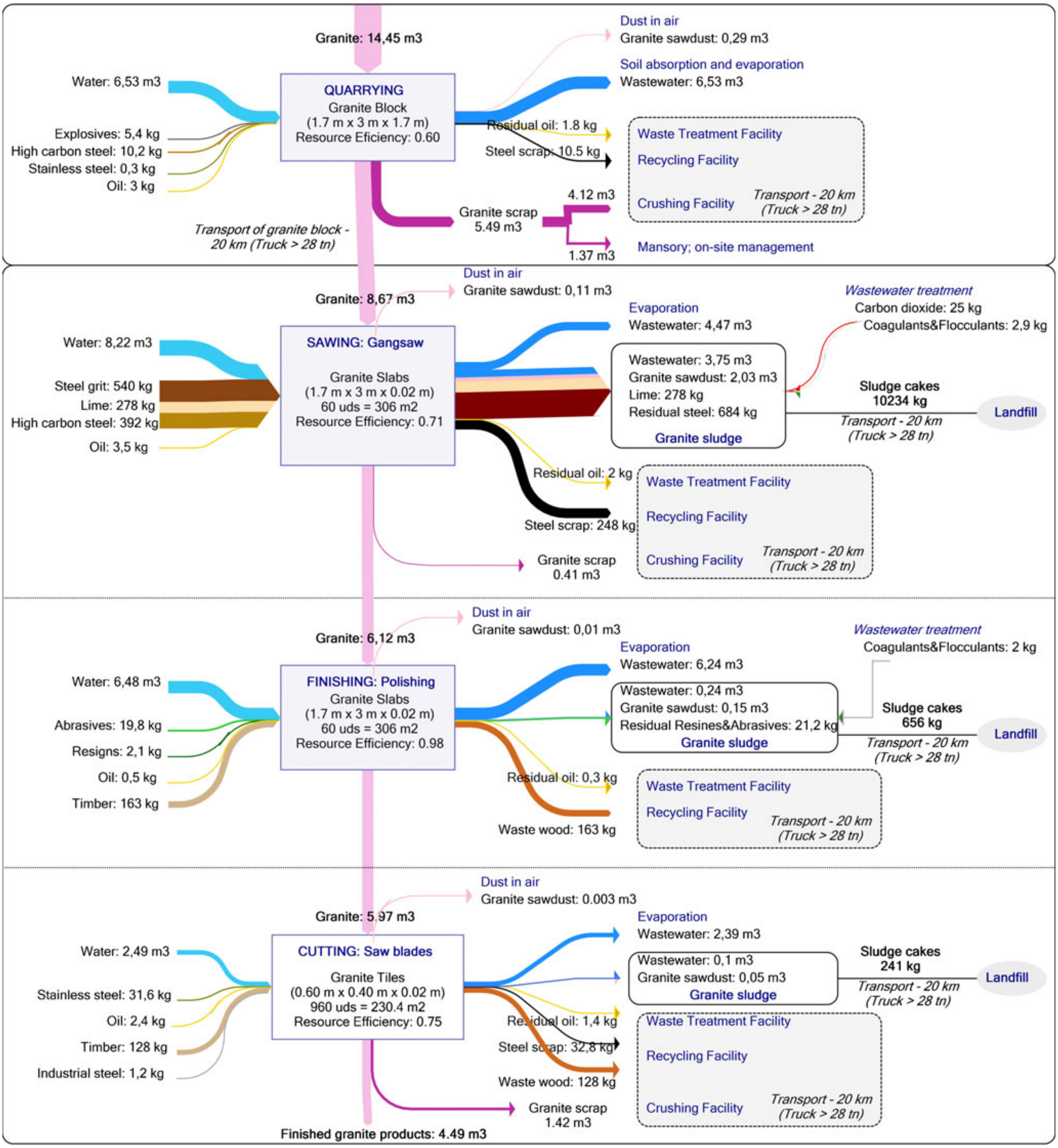

Fig. 2 Water and material balances related to quarrying a granite block and processing it into finished tiles

production chain. The data related to the finishing stage refer to polishing. All inputs and outputs associated with the different unit processes are disaggregated by types of elements in the ESM 4 (quarrying) and the ESM 5 (processing), including the standard deviation of the data. Inputs and outputs related to the sandblasting, flaming and bush-hammering finishing processes are shown in the ESM 6. The LCI data of finishing processes are analysed on a square meter basis in Section 3.2.

The amount of diesel required to transport a granite block to a processing facility and wastes to treatment facilities and landfills (20 km; truck, >28 tonnes) are not included in the LCI data. It is assumed that ancillary materials would be transported an average distance of 50 km from the production

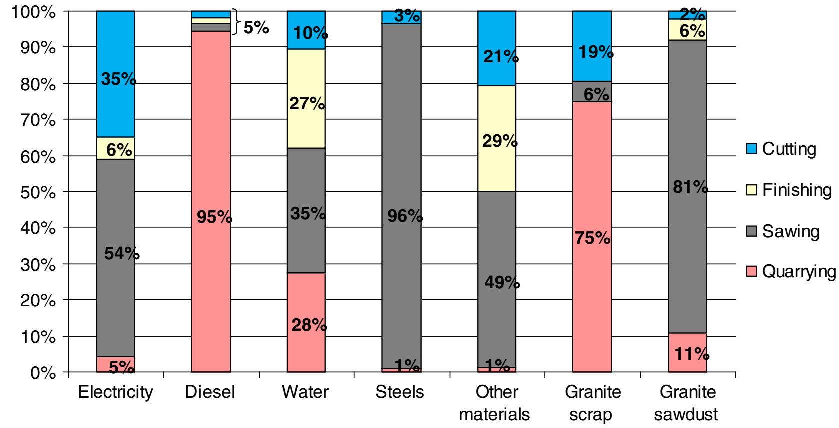

Fig. 3 Relative contribution of each unit process to the most significant inputs and outputs of the granite production chain

plants to the granite quarries and processing facilities. Diesel requirements for transportation of ancillary materials are also excluded from calculations.

Energy consumption Over 6.5 MWh of electricity and 5.3 GJ of diesel are required to quarry and process a granite block into finished tiles. Granite quarrying requires a minor electricity input but accounts for almost all diesel requirements in the granite production chain. The majority of energy consumed in quarries is associated with on-site transportation operations, including the movement of commercial granite blocks and granite scrap to storage and their loading onto trucks for shipment to processing or crushing facilities. The second largest consumers of diesel are operations related to drilling. The operations related to stone cutting with diamond monowire machines account for a substantial share of the electricity requirements in granite quarrying. Granite processing is the most electricity-intensive stage in the granite production chain. Diesel represents a minor energy input as transport operations are significantly reduced; the operation area is reduced, processing operations are highly mechanised, and the weight of granite that is transported between unit processes is successively reduced due to material losses in the form of sawdust, which is removed by the stream of cooling water used in production. Granite sawing is the most electricity-intensive unit process in the processing stage. Gang saws are large heavy-weight electrically powered machines. The lowering speed of a gang saw ranges from 3 to 5 cm h^{-1}. According to the dimensions of the granite block analysed, the sawing process requires 34 to 57 h. Therefore, a substantial amount of electricity is consumed during its operation. The second electricity-intensive process is comprised of cutting granite slabs into tiles. Diamond disc saws offer suitable performance due to the content of the synthetic diamond at the periphery of the discs, which reduces the time required to cut the stone and the related electricity requirements. The finishing process is the least electricity intensive. The energy force to be applied on the surface of the stone is less relevant than the energy force required in granite sawing and cutting as they are a more aggressive process. The finishing process is also significantly fast (ESM 2).

Water consumption A continuous stream of cooling water is required to dissipate the heat generated by the different unit processes, as sufficiently elevated temperatures can cause significant machine and material damage. A total volume of 23.7 m^3 of water is required for quarrying and processing a granite block into finished tiles. Groundwater, surface water, and tap water are utilised during granite production, which accounts for 35 % (8.3 m^3), 19 % (4.5 m^3) and 46 % (10.9 m^3), respectively (see ESM 4 and 5). Groundwater and surface water are pumped from natural reservoirs that are located near industrial facilities. Granite quarrying consumes over a quarter of the total water demand in the production chain. Surface water is the main source of water in quarrying. It is comprised of rainwater that accumulates in natural reservoirs located near the quarries at high altitudes, which facilitates water pumping due to gravity force. The remaining water requirements are driven by groundwater. No water recycling systems are implemented in the quarries. All water inputs leave the quarrying process as wastewater, which evaporates and is drained by the soil. The processing stage is significantly more water intensive. Tap water is the primary source of water. Granite sawing is the most water-intensive process, accounting for over one third of the total water demand of the production chain. In the process of granite sawing, the function of the water input is to refrigerate the steel blades used to erode the stone and remove the fines generated during the process. The water also contains an abrasive mixture composed of steel grit, lime and an amount of granite fines that are generated in the process. The abrasive mixture is required to produce stone cutting as a result of the thrust force generated by the steel blades. In the polishing and cutting processes, the cooling water does not contain any abrasive mixtures. Note that although it is shown separately in Fig. 2, to provide information on the different compositions of the wastewater generated by each unit process, wastewater is transported to the same water treatment line. The water utilised in the processing facilities circulates through a closed-loop

circuit. Wastewater is recycled after the cleaning process. The water consumption in the processing facilities corresponds to required additions supplied to the circuit to compensate for water losses. Approximately 76 % (13.1 m^3) of the water inputs leave the processing facilities as evaporation; the remaining 24 % (4.1 m^3) leave the facilities as moisture content in the granite sludge cakes, which are generated after the wastewater cleaning process (see ESM 2). The volume of water evaporated in each unit process relies on the water flow required in production, the manner in which the water is projected over the stone and the manner in which the wastewater is collected through the water circuit during cleaning operations.

Ancillary material consumption Nearly 1.6 tonnes of ancillary materials are required to quarry and process an entire granite block into tiles; steel accounts for 60 % (974 kg). The consumption of steel is determined by the service life of the elements used in drilling and cutting operations. Quarrying operations require only 1 % (19 kg) of the total material requirements. The predominant ancillary materials consumed in granite quarrying are high-carbon steel (drill rods and drill bits) and stainless steel (diamond wire). The amount of explosives used per unit of commercial granite block produced is low as small quantities are applied to minimise material loss. The demand of ancillary materials is mainly determined by the stage of granite processing, for which sawing is the most material-intensive unit process. Over three quarters of the materials required in the processing stage are determined by the sawing process. By distinguishing the input of wood, the cutting process is the second material-intensive process due to the requirements of stainless steel for the replacement of residual diamond disc saws. The amount of synthetic diamond per disc saw is not considered within the LCI as no information was available. The input of wood in the finishing and cutting processes relates to bars, boards, tips, pallets and bundles used for transporting granite slabs and tiles between unit processes and their subsequent packaging. Steel slings are used to hold the material once they are palletised and boxed. Oil consumption in quarrying and processing relate to maintenance operations of the production machinery.

Granite wastes—resource efficiency Granite quarrying has a resource efficiency of 0.60, whereas granite processing has a resource efficiency of 0.52. It yields a total resource efficiency of 0.31. For every net unit of granite tiles, 3.2 units of raw granite require quarrying. Granite waste is divided into granite scrap, generated due to stone breakage or stone squared, and granite sawdust caused by the friction of drilling and cutting tools on the surface of the stone. The total amount of granite waste produced represents 9.96 m^3 (26.9 t), of which 74 % is in the form of granite scrap. Granite scrap generated in the quarrying stage accounts for three quarter of the total amount of granite scrap produced in the entire granite production chain. Nearly 25 % of the produced granite scrap has sufficient size and quality to be used for producing masonry products, whereas the remaining granite scrap is sent to a crushing facility to produce aggregate for construction. The processing stage accounts for 42 % of all granite wastes generated in the granite production chain. However, resource efficiencies values indicate that granite processing is the first generator stage of granite wastes in relative terms. Granite sawdust is the first source of granite waste of the processing stage, which is mainly determined by the sawing process that contributes to over 80 % of the total sawdust generation from the granite production chain. Approximately 5 % of granite sawdust is considered to be emitted to the air, whereas the remainder is contained in the granite sludge cakes. This relationship is also attributable to the polishing and cutting processes. The total amount of sawdust produced during granite sawing relates to the number and thickness of steel blades used to saw a granite block (see ESM 3). In the cutting process, minimal sawdust is produced but a relevant amount of raw granite is lost as scrap. The dimensions of the granite tiles significantly affects the amount of granite scrap that is produced as the dimensions of the granite slabs to be cut are defined by the dimensions of the granite blocks, which are essentially fixed. Granite scrap produced during the processing stage is also sent to a crushing facility to produce aggregates.

Other wastes All water and material inputs from granite quarrying and processing leave the unit processes as liquid and solid wastes. Only pollutant emissions in the form of granite sawdust are accounted. The amount of explosives utilised in quarrying leaves the unit process as released energy and particulates that are dispersed to the area. In the sawing process, approximately 37 % of the steel blades (carbon steel) are assumed eroded by friction and become steel fines that are removed among the worn steel grit and the lime. All inputs of steel grit and lime leave the sawing process as residual fines. Eroded steel blades become steel scrap. In polishing, inputs of abrasives used in production leave the unit process as solid waste, which are subsequently contained in the granite sludge cakes. Regarding resins, 70 % of the input leaves the unit process in the wastewater sent to the cleaning treatment, whereas the remainder is contained in the surface of the polished granite slabs. A proportion (≈40 %) of the inputs of oil used in maintenance operations is considered to be lost through leaks in the machinery.

3.2 Life cycle inventory dataset per square meter of finished granite tiles

The LCI data of the production chain from cradle to gate of 1 m^2 of finished granite tiles are presented in Table 2. The

inputs and outputs related to the finishing processes of polishing, sandblasting, flaming and bush hammering are presented. Inputs and outputs of each unit process (Table 1, Fig. 2, ESM 4-6) have been allocated to a square meter basis according to the net production volume of finished granite tiles, which account for 230.4 m^2 per processed granite block. The total LCI results refer to the sums of the input and output data of granite quarrying, sawing, polishing and cutting. Input and output data are aggregated per input categories. The complete dataset is disaggregated by type of elements in the ESM 7.

The LCI results indicate that 28 kWh of electricity, 23 MJ of diesel, 103 l of water and 7 kg of ancillary materials are required per square meter of polished granite tiles. The amount of granite waste corresponds to 117 kg m^{-2}. The relationship between the inputs and outputs related to the different finishing processes is mainly examined in this section. The data in Table 2 indicates that flaming is the most energy-intensive finishing process. In contrast with polishing, the energy demand of flaming is mainly driven by propane. An input of electricity is required to operate the flaming machinery, but it is a minor energy demand. The input of diesel relates only to transportation operations, which are equivalent in all finishing processes as the weight of the granite slabs to be handled is the same as well as the average distance travelled by them. The energy demand for bush-hammering finishes, which can substitute for flaming finishes in outdoor flooring according to required anti-slipping levels, is reduced as propane is not required and electricity demand is 11 % lower. Sandblasting, which can substitute for polishing finishes in indoor and outdoor cladding applications, requires 64 % lower electricity demand than polishing. With regards to water consumption, only polishing and flaming finishing processes require an input of cooling water during production. The volume of water required for polishing is a factor of 1.9 higher than the volume of water required for flaming, as it is a significantly more aggressive process. The promotion of sandblasted granite tiles instead of polished granite tiles as well as the promotion of bush-hammered granite tiles instead of flamed tiles can conserve 28 and 15 l of water per square meter. With regards to materials demand, the sandblasting finishing process is the largest consumer of materials due to the requirement of silica sand (≈1 kg m^{-2}), but it is the only material input that is directly required in production. Polishing is the only finishing process that requires coagulants and flocculants for cleaning the wastewater that is generated during the process. Granite splinters generated in the flaming finishing process are easily decanted during the wastewater treatment process; therefore, the addition of coagulants and flocculants are not essentially required. No ancillary materials are required during granite flaming. Regarding the bush-hammering finishing process, it is assumed that the inputs of bushes to be allocated per square meter of granite tiles are almost negligible due to its anticipated long service life. The inputs of wood, oil and grease are assumed to be equivalent for all finishing processes.

4 Discussion

The natural properties of granite, which define its high performance as a construction material, are also the main reasons that determine the energy, water and material requirements of its production chain. The standard classification of natural stones for construction, UNE-EN 12670 (2003), defines granite as a natural compact stone that consists of a mass of minerals, such as quartz and feldspar with hardness values between 5 and 7 on the Mohs scale. Heavy equipment is therefore required to remove a granite block from a natural deposit and further processing it into suitable pieces for construction. The LCI results demonstrated that the most significant inputs demanded by the granite production chain consist of electricity, diesel, water and steels. Electricity consumption is basically related to stone-cutting operations addressed in granite processing stage. The electricity mix in the region or country where granite blocks are processed into slabs and tiles will significantly influence the definition of the environmental burden of the embodied energy of granite products. In countries with high proportions of renewable or low-carbonised sources in the national electricity mix, granite processing will contribute to produce granite products with a lower environmental burden than granite processed in countries with high carbonised electricity systems. Diesel consumption is basically determined by on-site transportation and drilling operations addressed in granite quarrying. Well-planned transportation management and well-considered drilling operations can provide advantages to reduce diesel consumption in quarries and consequently at the entire granite production chain.

Granite production is a high water-intensive industrial activity, specially the granite processing stage even though water circulates through a closed-loop circuit. A half of the total water requirements are pumped directly from natural sources. The presence of groundwater and surface water reservoirs near quarries and processing facilities are crucial to the development of industrial activity. Special attention should be given to specifically analysing the environmental impact of granite quarrying and processing in geographical contexts with water scarcity and high-quality natural water reservoirs.

Special attention should also be given to analysing the environmental burden associated with the different types of steel used in granite production. Approximately 30 % of all inputs of steel used in the granite production chain become steel scrap, which is sent to recycling plants to produce recycled steel.

Regarding resource efficiency, over two thirds of the total volume of granite quarried is wasted in the form of granite scrap and sawdust. The amount and type of granite waste is

Table 2 LCI data of the production chain from cradle to gate of 1 m^2 of finished granite tiles with dimensions of 60 cm×40 cm×2

Industrial flows	Inputs	Quarrying*	Processing						Total (*)
			Sawing*	Finishing				Cutting*	
				Polishing*	Sandblasting	Flaming	Bushnhammering		
Energy	Low voltage electricity (kWh)	1.26E+00	1.54E+01	1.73E+00	6.29E−01	3.74E−02	3.32E−02	9.90E+00	2.83E+01
	Diesel (MJ)	2.19E+01	4.42E−01	4.12E−01	4.12E−01	4.12E−01	4.12E−01	4.11E−01	2.32E+01
	Propane (MJ)	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.55E+01	0.00E+00	0.00E+00	0.00E+00
Water	Cooling water (kg)	2.83E+01	3.57E+01	2.81E+01	0.00E+00	1.51E+01	0.00E+00	1.08E+01	1.03E+02
Ancillary materials	Explosives (kg)	2.36E−02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.36E−02
	Steels (kg)	4.54E−02	4.04E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.42E−01	4.23E+00
	Lime (kg) / Silica sand (kg)	0.00E+00	1.21E+00	0.00E+00	1.01E+00	0.00E+00	0.00E+00	0.00E+00	1.21E+00
	Abrasives and Resigns (kg)	0.00E+00	0.00E+00	9.48E−02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.48E−02
	Timber (kg)	0.00E+00	0.00E+00	7.08E−01	7.08E−01	7.08E−01	7.08E−01	5.56E−01	1.26E+00
	Coagulants and flocculants (kg)	0.00E+00	1.24E−02	8.54E−03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.10E−02
	Oil and grease (kg)	1.28E−02	1.53E−02	2.08E−03	2.08E−03	2.08E−03	2.08E−03	1.04E−02	4.06E−02
	CO_2 (kg)/O_2 (kg)	0.00E+00	1.08E−01	0.00E+00	0.00E+00	1.32E+00	0.00E+00	0.00E+00	1.08E−01
Granite —raw material	Granite (kg)—gross	1.69E+02	1.02E+02	7.17E+01	7.17E+01	7.17E+01	7.17E+01	6.99E+01	1.69E+02
Industrial flows	Outputs	Quarrying*	Sawing*	Polishing*	Sandblasting	Flaming	Bush−hammering	Cutting*	Total (*)
Granite product	Granite (kg)—net	1.02E+02	7.17E+01	6.99E+01	6.99E+01	6.99E+01	6.99E+01	5.27E+01	1 m^2
Granite wastes	Granite sawdust (kg)	3.37E+00	1.26E+00	8.96E−02	1.79E+00	8.96E−02	1.79E+00	3.22E−02	4.75E+00
	Granite scrap (kg)	6.44E+01	4.78E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.66E+01	8.58E+01
	Granite sludge (kg) mix of elements	0.00E+00	4.44E+01	2.85E+00	0.00E+00	2.26E+00	0.00E+00	1.05E+00	4.83E+01
Wastewater	Wastewater (kg)—evaporated	2.83E+01	1.94E+01	2.71E+01	0.00E+00	1.46E+01	0.00E+00	1.04E+01	8.52E+01
Solid wastes	Wastes (kg)—mix of elements	5.33E−02	1.08E+00	7.09E−01	1.72E+00	7.09E−01	7.09E−01	7.04E−01	2.55E+00

*Unit processes considered to define the total inputs and outputs per square meter of finished granite tiles

dependent on the type of machinery used in production and the dimensions of the product to be produced. As explosives and drilling machines are used during granite quarrying, a substantial amount of granite is wasted as scrap compared with granite processing, in which a higher amount of granite is wasted as sawdust. Granite scrap is used for producing masonry products and aggregates. Granite scrap, therefore, become a by-product of the granite production chain. According to the ISO 14044 (2006), a clear distinction between the main products and by-products is essential to allocate the inputs and outputs and subsequently analyse the environmental impact of product systems. The main products are the products for which the industrial process is primarily operated and, thus, determine the production volume of the industrial activity. By-products are marketable products for which the process is not primarily operated due to their low market price or because they accumulate as surplus. In this case study, all inputs and outputs related to the granite production chain are attributed to the main production line that relates to the generation of commercial granite blocks during granite quarrying and granite slabs and tiles during granite processing. The produced volume of granite scrap is not associated with any energy, water or material inputs. However, the input and output flows of the granite production chain can be split up between granite tile and granite scrap production by applying a mass-based allocation method. For a net production of 12,131 kg of finished granite tiles (≈230.4 m^2), a total number of 19,732 kg of granite scrap is generated per quarried and processed granite block. If inputs and outputs are allocated according to these totals, 38 % of all inputs and outputs of the granite production chain would be allocated to granite tile production and the remaining 62 % to granite scrap generation. This method of allocation is not a reasonable approach. Instead, the relative mass contributions of both granite main products and scraps to each unit process of the granite production chain should be considered. According to this method, the inputs and outputs related to granite quarrying, sawing, finishing and cutting should for respectively 61, 94, 100 and 76 % be allocated to granite main products and for 39, 6, 0 and 24 % to granite scrap generation. Additional processing of granite scraps into masonry products and aggregates should be calculated later and assigned to granite scraps. The application of an economic allocation method is not a feasible option due to the significant difference in the price of the materials. The price of a tonne of rough granite amounts to more than 100€, whereas a tonne of finished granite has a price of over 350€. Granite aggregates generated from processing scraps are priced less than 8€/tonne. The generation of granite sawdust can therefore be considered as the only source of material lost in the granite production chain. One of the most important research and innovation areas related to granite processing is the identification of strategies for reducing sawdust generation using technological improvements or promoting the use of granite sludge as a raw material in industrial applications. As the use of granite sludge as by-product is still evolving with regards to research and development, it is disposed in landfills or used as land-filler material in mines.

5 Conclusions

The LCIs provide all the relevant information required to address a complete life cycle impact assessment of granite production and products. The LCI data are flexible and easily managed by users due to its disaggregation into unit processes. The LCI data can be employed to analyse the environmental burden associated with intermediary granite products, such as granite blocks, sawn granite slabs and finished granite slabs, as well as the environmental burden of finished granite tiles.

The geometry of the pieces of granite to be produced is a decisive factor for the different inputs and outputs of the production chain, for example sawdust generation. The total production of granite sawdust during sawing is inversely proportional to the thicknesses of the granite slabs to be produced, whereas the opposite scenario occurs in the cutting process. This relationship is an important aspect to be considered as it may also affect the energy, water and material demands during granite sawing and cutting. Further research is required to analyse the effect that the dimensions, especially the thickness, of the granite products have on the different inputs and outputs of the production chain. It will also be important to achieve consistency in the functional units considered for data collection and calculation in order to develop directly comparable LCIs. The inputs and outputs should also be well disaggregated into the different unit processes to facilitate the analysis of LCI results and the adaptation of data to different functional units, whenever that is possible.

An initial analysis of the LCI results indicated that granite sawing is the most ecologically relevant unit process of the granite production chain. Cleaner production strategies that focus on the sawing process can contribute to significantly reduce the environmental interventions related to the granite production chain. Further research is required to compile input and output data related to alternative sawing technologies, such as the use of diamond multiwire saw machines that are achieving higher relevance in the granite industry and seems to be a suitable strategy for improving the environmental performance of the production chain. Industrial ecology studies focused on the management of granite sludge can also offer interesting environmental findings and opportunities for the granite industry.

The compilation of LCIs related to the granite production chains from highly competitive countries, such

as China, India and Brazil, should also be accomplished in the near future to transparently compare the environmental performance of granite products produced in the major granite industries of the world, define global strategies to improve the environmental performance of the granite sector, highlight the relevance of those industries in which cleaner production techniques are implemented and promote the green procurement of environmentally improved granite products.

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